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Estimation of sunshine duration from the global irradiance measured by a photovoltaic silicon solar cell

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ABSTRACT

Sunshine duration can be estimated using photovoltaic solar cells instead of conventional pyranometers or pyrheliometers, which are more expensive and therefore not suitable for low cost measurement applications in developing regions. A one-year meteorological dataset from Nicosia (Cyprus) including direct irradiance, global irradiance from a pyranometer and global irradiance from a reference PV cell was used to calculate sunshine duration following the WMO pyrheliometric method and three pyranometric methods by WMO Slob and Monna, Hinssen–Knap and Olivieri. Pyranometric algorithms were adapted to the tilted pyranometer and reference solar cell. Main results indicate that all the pyranometric algorithms underestimated sunshine duration over the span of a year in Cyprus in comparison with the reference pyrheliometric method; and that results between the pyranometer and the solar cell were comparable. The PV silicon solar cell is capable of measuring sunshine duration on a daily basis with an uncertainty similar to the obtained with a pyranometer when using the Olivieri algorithm.

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1. Introduction

The World Meteorological Organisation (WMO) [1] defines sunshine duration (*SD*) as the number of hours for which the direct solar irradiance is above 120 W/m^2. This type of measurement is often used in low cost renewable energy applications, for example in solar water purification processes such as solar disinfection (SODIS) [2–5]. A common approach to SODIS in developing countries uses plastic bottles exposed to the sun to purify water. It requires that for a sunny day, 6 h of sunshine is needed to treat the water and make it safe to drink. In cloudy conditions, the time required for the water purification increases to 2–3 days. Therefore,

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a low-cost sensor capable of estimating the sunshine hours would be suitable for SODIS water treatment and would improve its effectiveness and spread in developing areas [6–9].

The aim of this study is *to determine if a photovoltaic (PV) silicon solar cell can be used to measure sunshine duration*, and therefore serve as a sensor for low-cost solar technology applications such as solar water purification. To evaluate the suitability of this approach, the different algorithms proposed by the WMO for *SD* calculation from direct irradiance, global irradiance and diffuse irradiance will be compared using a pyrheliometer, pyranometer and silicon cell.

The algorithms that use only global irradiance from a pyranometer will be applied to the case of global irradiance data that come from a PV silicon solar reference cell [10]. A comparison will be made between the sunshine duration calculated by the PV cell with the *SD* values obtained from data from the pyranometer and pyrheliometer. The correlation between the data from the cell and the data from the pyranometer, as well as possible limitations and possible correction factors, will be studied in order to conclude whether the cell is suitable or not for the measurement of sunshine duration.

2. Sunshine duration measurement

There are different methods to determine the sunshine duration according to the WMO [1], including direct measurement with the Campbell–Stokes recorder, the pyrheliometric method using direct irradiance from a pyrheliometer, or pyranometric algorithms using the global irradiance from a pyranometer. There are also additional pyranometric methods not adopted yet by the WMO but that are well-reviewed in the literature aiming to improve the pyranometric algorithm used by the WMO [11–13].

2.1. Campbell–Stokes sunshine recorder

This instrument was introduced in 1880, and is composed of a glass sphere that concentrates the solar radiation beam onto a graduated paper card that burns according to a sunshine intensity threshold. The sunshine duration is read from the total burn length [14,15]. The WMO considers that it does not provide accurate data as the burns are subjected to errors caused by possible mounting adjustments problems and to the fact that the burns depend heavily on the card temperature and humidity [1,16].

2.2. Pyrheliometric method

The sunshine duration definition given by the WMO as '*the number of hours for which the direct solar irradiance is above 120 W/m²*' requires a more accurate method than the Campbell–Stokes recorder. In this regard, direct solar irradiance is measured by a pyrheliometer held normal to the sun by a sun tracker and monitored automatically [17]. A pyrheliometer measures only the direct and circumsolar irradiance by using a thermopile with a broadband spectral response (typically from below 200 nm to 4000 nm) and with a narrow aperture. It requires continuous sun tracking. The sunshine duration is then obtained by integrating the time over the day length during which the direct solar irradiance exceeded the threshold of 120 W/m^2. In summary, the data required and the sunshine duration calculation using the pyrheliometric method are as follows:

- *Data*: Direct solar irradiance from a pyrheliometer with a resolution of 1 min.
- *Sunshine duration*: Period composed by the sub-periods in which the direct solar irradiance is above 120 W/m^2. The sub-period is 1 min.

2.3. Pyranometric methods

Other methods used by the WMO are based on the measurement of global irradiation using a pyranometer. A pyranometer consists of a thermopile with a broadband spectral response; similar to a pyrheliometer, but in this case the aperture is not narrowed but widened using a semispherical glass dome. If a shading ring or a shading ball is used to block the direct radiation reaching the pyranometer the diffuse radiation can be obtained. The shading ball requires full two-axis sun tracking, whereas the shading ring requires weekly elevation adjustment.

The relationship between direct, global and diffuse solar radiation is

$$I \cos\theta = G - D \tag{1}$$

where I is the direct solar radiation normal to the plane of measurement, $I\cos\theta$ is the horizontal component of the direct solar radiation, θ is the solar zenith angle, G is the global solar horizontal radiation, and D is the diffuse solar horizontal radiation.

If there are ***two pyranometers*** available, one for global solar radiation and one for diffuse solar radiation then the WMO method can be used to calculate the direct solar radiation component by using the relationship given in Eq. (1). Sunshine duration can then be calculated by filtering for periods where the threshold of 120 W/m^2 is exceeded. Therefore, this method uses

- *Data*: Global solar irradiance from a pyranometer and Diffuse solar irradiance from a pyranometer with shading ring or shading ball and tracker, with 1-min resolution.
- *Sunshine duration*: Period composed by the 1-min sub-periods in which the direct solar irradiance, calculated as $I = (G-D)/\cos\theta$, is above 120 W/m^2.

However, if there is only ***one pyranometer*** available, measuring global horizontal solar radiation, then the sunshine duration calculation is not so straightforward. Several algorithms have been proposed by different authors [11–13] that use the global horizontal and other common parameters, such as the latitude, longitude, cloud cover, turbidity, temperature, etc. Some of these algorithms are described in the next sub-section. Of these, the WMO currently uses the Slob and Monna algorithm. Slob and Monna developed this algorithm in 1991 [18]. It uses the mean, minimum and maximum of global solar radiation in a 10-minute interval. It is based on an estimation of the direct (Eq. (2)) and diffuse (Eq. (3)) components for cloudless conditions, which depends on the Linke turbidity factor T_L [19] (related to the trace gases and aerosols in the atmosphere), the solar constant ($I_0 = 1367\ W/m^2$) and the cosine of the solar zenith angle ($\mu_0 = \cos\theta$). These estimations are based on a three year dataset in the Netherlands (1986–1989) and are as follows:

$$I = I_0 \exp(-T_L/(0.9 + 9.4\mu_0)) \tag{2}$$

where I is the parameterised estimation of direct solar irradiance for cloudless conditions, I_0 is the solar constant, T_L is the turbidity factor and μ_0 is the cosine of the solar zenith angle.

$$D/G_0 = \begin{cases} 0.2 + \mu_0/3 & \text{for } 0.1 \le \mu_0 \le 0.3 \\ 0.3 & \text{for } \mu_0 \ge 0.3 \end{cases} \tag{3}$$

where D is the parameterised estimation of diffuse solar irradiance for cloudless conditions and G_0 is the horizontal radiation in the atmosphere ($G_0 = I_0\mu_0$).

The algorithm compares the measured global solar irradiance G with the lower limit for cloudless conditions, which is $I\mu_0 + D$. This comparison is conducted with all the values normalised by G_0. Fractional values of sunshine f are then calculated for 10-min intervals (0 – no sunshine at all, 1 – only sunshine, between 0 and

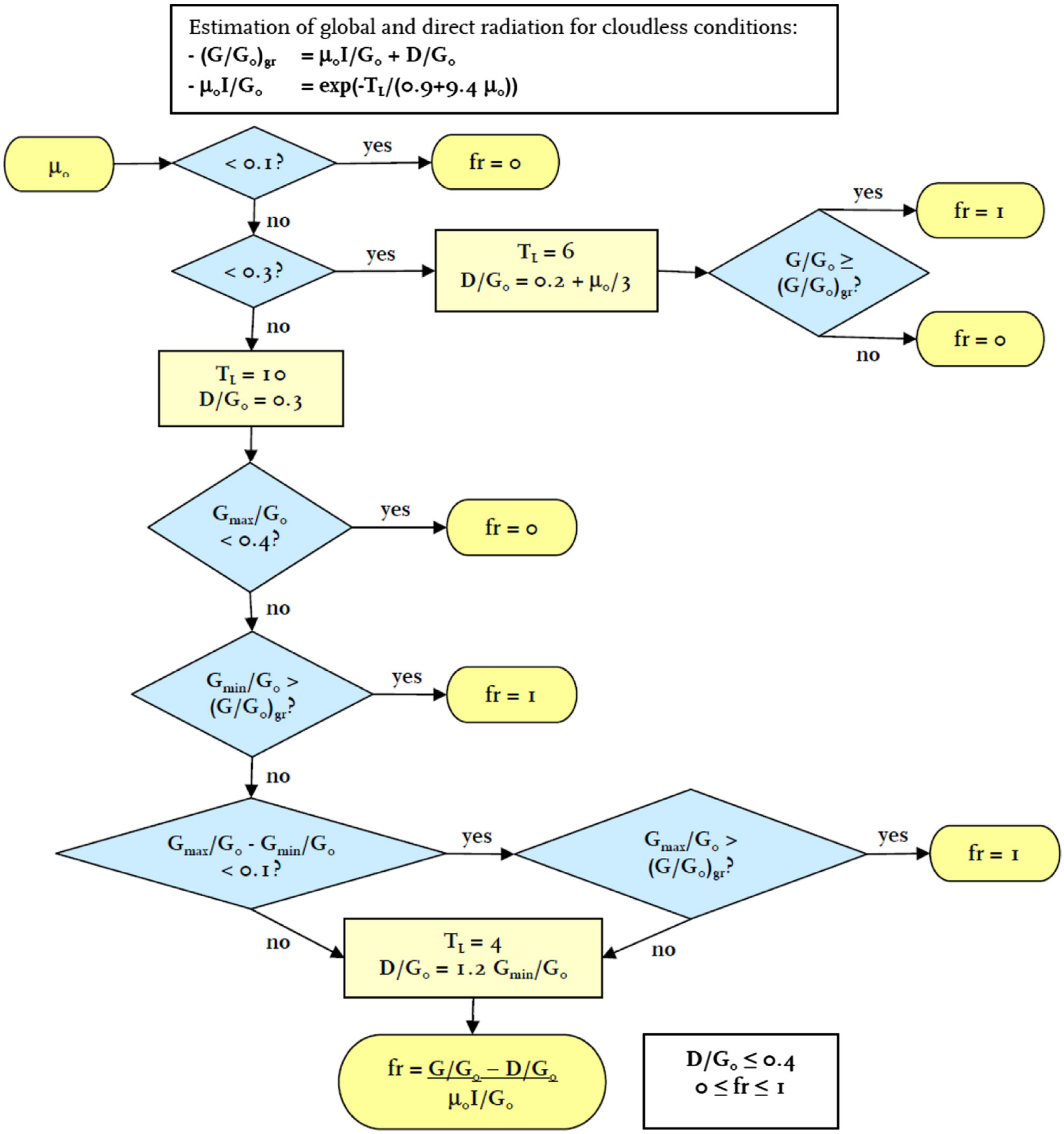
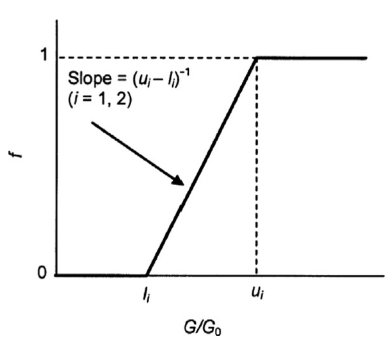


Fig. 1. The Slob and Monna algorithm to estimate sunshine duration from one-single pyranometer readings of global horizontal radiation. Fractional values of sunshine *f* are calculated for 10-min intervals, comparing with estimated values of direct and diffuse radiations for cloudless conditions [5].



$$
\begin{array}{llll}
\mu_0 < 0.3: & G/G_0 < l_1 & \rightarrow & f = 0 \\
 & l_1 \leq G/G_0 < u_1 & \rightarrow & f = (G/G_0 - l_1)(u_1 - l_1)^{-1} \\
 & G/G_0 \geq u_1 & \rightarrow & f = 1 \\
\mu_0 \geq 0.3: & G/G_0 < l_2 & \rightarrow & f = 0 \\
 & l_2 \leq G/G_0 < u_2 & \rightarrow & f = (G/G_0 - l_2)(u_2 - l_2)^{-1} \\
 & G/G_0 \geq u_2 & \rightarrow & f = 1.
\end{array}
$$

Fig. 2. The Hinssen–Knap correlation algorithm, showing the linear relationship of sunshine duration with the mean global solar irradiance and the limits established for two different intervals depending on the sun elevation angle [2].

1 – partly sunshine, partly clouded), and sunshine duration *SD* is obtained by multiplying f by 10. The complete algorithm is shown in Fig. 1.

In summary, the pyranometric method used by the WMO with only a single pyranometer measuring global radiation uses

- *Data*: Global horizontal irradiance from a pyranometer.
- *Sunshine duration estimation*: Slob and Monna algorithm.

2.4. Other pyranometric methods

As we mentioned earlier, there are other pyranometric methods developed by researchers at different meteerological agencies from different countries. One of the most successful and accepted algorithms is the ***Hinssen–Knap algorithm***, developed by Hinssen and Knap in 2006 by adjusting the Slob algorithm [11,20]. The improved algorithm directly relates sunshine duration to 10-min mean measurements of global irradiance (Fig. 2). There is a lower limit l_i for G/G_0, and below which there is no sunshine ($f=0$), and upper limit u_i, and above which there is full sunshine ($f=1$). Between the limits, the sunshine duration is a linear function related to the normalised global irradiance. The algorithm has two different intervals depending on the sun elevation angle ($\mu_0<0.3$; $\mu_0\geq 0.3$). The optimum values for l_1, u_1, l_2 and u_2 need to be established by calculating the pyrheliometric fractional values of *SD* for 10-min intervals and representing against the normalised global irradiance G/G_0. For the dataset and location considered under their study, which corresponds to 1-year data at the station of Cabauw (Netherlands, 51.97°N and 4.93°E), the optimum values were of $l_1=0.4$, $u_1=0.5$, $l_2=0.45$ and $u_2=0.6$. These values should be calculated for new locations, especially when in different climatic areas.

In a recent report from 2011, Massen [13] has reviewed several pyranometric algorithms, including the Olivieri algorithm [21], the Slob and Monna, the Hinssen–Knap, the Louche ½ [22], the Campbell [23] and the Glover [24]. He uses the Hinssen–Knap as the reference algorithm for comparison, and concludes that amongst the other approaches, the most accurate and easy to use for calculating the sunshine duration in accordance with the WMO definition is the Olivieri one. In 2012, Vuerich et al. [12] also presented an evaluation of several pyranometric algorithms. The algorithms studied included those by Slob and Monna, and Olivieri, among others. They also concluded that the algorithm providing the best results, with less uncertainty, was the ***Olivieri algorithm***. This algorithm was developed at the Météo France in 1998 [12,21], and it compares the global irradiance to a threshold value that is a function of F, which represents a fraction of the global irradiance in clear sky in average conditions of turbidity (Fig. 3). The coefficients A and B are specific for each location. Météo France calculated an empirical table including the coefficients for different location latitudes.

A description of the main methods to calculate sunshine duration using different equipments has been presented: first, by means of a Campbell–Stokes recorder; second, using directly a pyrheliometer (direct irradiation) and a sun tracker; third, with the pyranometric method using two pyranometers (global and diffuse irradiations); and finally, using just one pyranometer measuring global irradiation, presenting three different algorithms in detail.

3. Estimation of *SD* from global solar irradiance measured by a solar cell

All the methods to calculate *SD* described previously are suitably accurate but they require expensive equipment such as a pyrheliometer, a sun tracker or a pyranometer, which is affordable for a meteorological weather station but not for day-to-day applications in developing countries. In the case being considered in this paper, solar water purification systems in developing countries need low cost sensors with an acceptable performance, so a trade-off between cost and performance must be achieved.

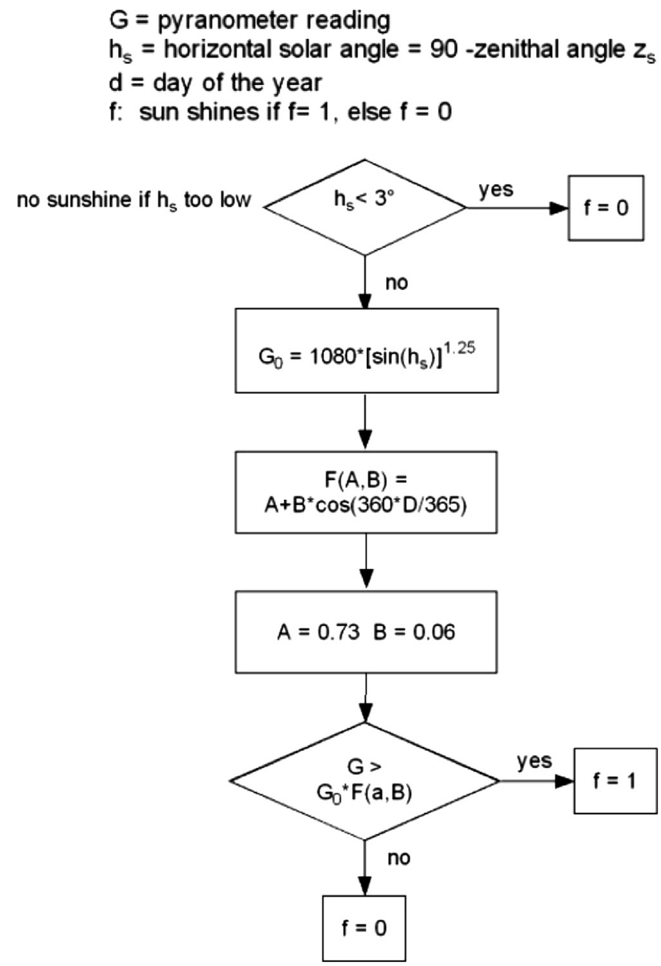


Fig. 3. The Olivieri correlation algorithm [4], estimating sunshine duration on 1-min basis comparison of global horizontal solar radiation with a threshold function of a fraction F of the global irradiance in clear sky in average conditions. Values of A and B are specific for each location, for this case they correspond to a latitude of 44°N.

A solar cell could be used to measure sunshine duration at low cost as it can measure incident solar radiation according to its spectral response. However, the solar cell spectral response is not broadband but limited according to the energy bandgap (till 1100 nm for a silicon solar cell). The other limitation is that the spectral response is not flat as in a thermopile, but with a maximum responsivity in the near-infrared. So the output depends on the solar radiation spectrum; and the WMO does not advocate the use of sunshine duration detectors based only on purely silicon photovoltaic solar cells because these spectral variations are a source of error [1]. Other limitations include the reduced field-of-view in comparison with a pyranometer and the annual degradation of a solar cell (~1% for monocrystalline silicon cells) [25–28].

In this work, an attempt is made to quantify the effect of these spectral variations in comparison with a pyranometer and a pyrheliometer when calculating *SD*. The objective is to determine if the *SD* calculated by a solar cell in relation to a pyranometer is well-correlated or not, and if it would be suitable for low-cost applications despite the expected performance degradation.

3.1. Methodology

Using a 1-year dataset with direct solar radiation data from a pyrheliometer mounted on a sun tracker, global solar radiation from a pyranometer and global solar radiation from a calibrated silicon photovoltaic solar cell, the sunshine duration was calculated using the pyrheliometric method and three of the pyranometric methods.

The sunshine duration calculated from the pyrheliometer, SD_{Pyrh}, was used as the reference data. The three pyranometric algorithms used were the Slob and Monna, the Hinssen–Knap and the Olivieri. They were applied to the global data provided by the pyranometer, calculating sunshine durations, SD_{Slob_Pyr}, SD_{Hins_Pyr} and SD_{Oli_Pyr}. They were also applied to the global data from the silicon photovoltaic solar cell for comparison, obtaining SD_{Slob_Si}, SD_{Hins_Si} and SD_{Oli_Si}.

As both the pyranometer and the silicon photovoltaic solar cell were at a tilted angle facing directly south, and not in a horizontal plane, the algorithms were corrected to compare with a tilted surface. For Slob and Monna (and so for Hinssen and Knap), the estimations of direct normal and diffuse were corrected for a tilted surface with an angle β [29]

$$I_\beta = I \cos \nu \tag{4}$$

$$\cos \nu = \cos \gamma_s \cos \alpha_s \sin \beta + \sin \gamma_s \cos \beta \tag{5}$$

$$D_\beta = D \frac{1 + \cos \beta}{2} \tag{6}$$

$$G_\beta = I_\beta + D_\beta \tag{7}$$

where I_β is the estimated direct normal at the tilted surface; ν is the angle of incidence respect to the tilted surface; γ_s is the sun elevation angle; α_s is the solar azimuth, β is the tilt angle; D_β is the estimated diffuse radiation at the tilted surface; and G_β is the estimated global radiation at the tilted surface.

The global horizontal extraterrestrial irradiance G_0 was also substituted for the global extraterrestrial irradiance at tilted surface, $G_{0,\beta}$, using the incident angle ν, $G_{0,\beta} = I_0 \cos \nu$, for the three algorithms. Hinssen correlation optimum limits were established for the new solar radiation dataset, obtaining $l_1 = 0.1$, $u_1 = 0.8$, $l_2 = 2$ and $u_2 = 0.7$.

3.2. Solar radiation data

Solar radiation data was obtained from the meteorological station and photovoltaic installation from the Photovoltaic Technology Group at the University of Cyprus, Nicosia, Cyprus. Latitude is 35.2°N and longitude 33.5°E. The direct normal irradiance was measured by a Kipp&Zonen CH1 pyrheliometer and the global irradiance by a Kipp&Zonen CM21 pyranometer. The calibrated photovoltaic solar cell used as a global irradiance sensor is a monocrystalline silicon solar cell. Both the pyranometer and the calibrated cell are mounted at a tilt angle of 27.5°. Data are sampled and stored every minute [30].

One-year data were used for this study, from December 2011 to November 2012. Data quality was checked in order to first eliminate those days with technical problems, such as power losses, sun-tracking issues or data acquisition irregularities. Main problems leading to wrong or absent recorded data were related to the sun-tracker (67 days) and the data acquisition system of the photovoltaic solar cell (12 days), usually due to maintenance operations and software updates. A second quality control stage consisted of filtering to remove solar radiation data that might be erroneous, checking the physically possible limits of solar radiation and the extremely rare limits.

3.3. Results

Table 1 presents a summary of the yearly totals of *SD* for the different methods: pyrheliometric, the Slob and Monna pyranometric algorithm, the Olivieri pyranometric algorithm and the Hinssen pyranometric algorithm. The sunshine duration calculated by the pyrheliometer is 2171 h. The cumulative difference of the pyranometric algorithms over the year is provided, observing that the Hinssen and Knap algorithm gives the best estimation, with −145 h (−7%) and −61 h (−3%), for the pyranometer and the cell, followed by the Slob and Monna algorithm, −411 h (−19%) and −210 h (−10%), and the Olivieri algorithm, −457 h (−21%) and −372 h (−17%). All the algorithms underestimate sunshine duration over the span of a year.

On a daily mean basis, the Hinssen and Knap algorithm gives −0.4 ± 0.08 h/day (±20%) and −0.17 ± 0.11 h/day (±65%), the Slob and Monna algorithm provides −1.12 ± 0.05 h/day (±4%) and −0.57 ± 0.08 h/day (±14%); and the Olivieri algorithm gives −1.25 ± 0.06 h/day (±5%) and −1.02 ± 0.07 h/day (±7%). This means that the uncertainty for the Hinssen and Knap on a daily basis is extremely high and that either the Slob and Monna algorithm or the Olivieri are suitable for measuring sunshine duration when using the pyranometer. For the case of the solar cell, the most suitable algorithm on a daily basis is the Olivieri. The main conclusion of this analysis is that the silicon solar cell is capable of measuring sunshine duration on a daily basis with an uncertainty similar to the obtained with a pyranometer when using the Olivieri algorithm. For the other two algorithms, Hinssen and Knap and Slob and Monna, the uncertainty is considerably higher than the *SD* calculation from the pyranometer.

Fig. 4 shows the calculated daily sunshine duration of the three algorithms vs. the sunshine duration calculated by the pyrheliometer. On the left we can observe the results for the pyranometer and on the right for the Si photovoltaic cell. As discussed, the Olivieri algorithm gives the better adjustment with the pyrheliometer for the solar cell. All the algorithms underestimate the sunshine duration hours relative to the pyrheliometric sunshine duration. For the case of Slob and Monna, this is already

Table 1
Yearly totals of *SD* for the different methods: pyrheliometric, the Slob and Monna pyranometric algorithm, the Olivieri pyranometric algorithm and the Hinssen pyranometric algorithm (h/year), cumulative difference with pyrheliometric *SD* (h/year) and mean difference (h/day) and standard deviation (h/day).

Method	Instrument	*SD* (h/year)	Difference (h/year)	Mean difference (h/day)	Standard error of the mean (h/day)
Pyrheliometric	Pyrheliometer	2171	–	–	–
Slob and Monna	Pyranometer	1760	−411	−1.12	0.05
Hinssen and Knap	Pyranometer	2026	−145	−0.4	0.08
Olivieri	Pyranometer	1714	−457	−1.25	0.06
Slob and Monna	PV Si cell	1961	−210	−0.57	0.08
Hinssen and Knap	PV Si cell	2110	−61	−0.17	0.11
Olivieri	PV Si cell	1799	−372	−1.02	0.07

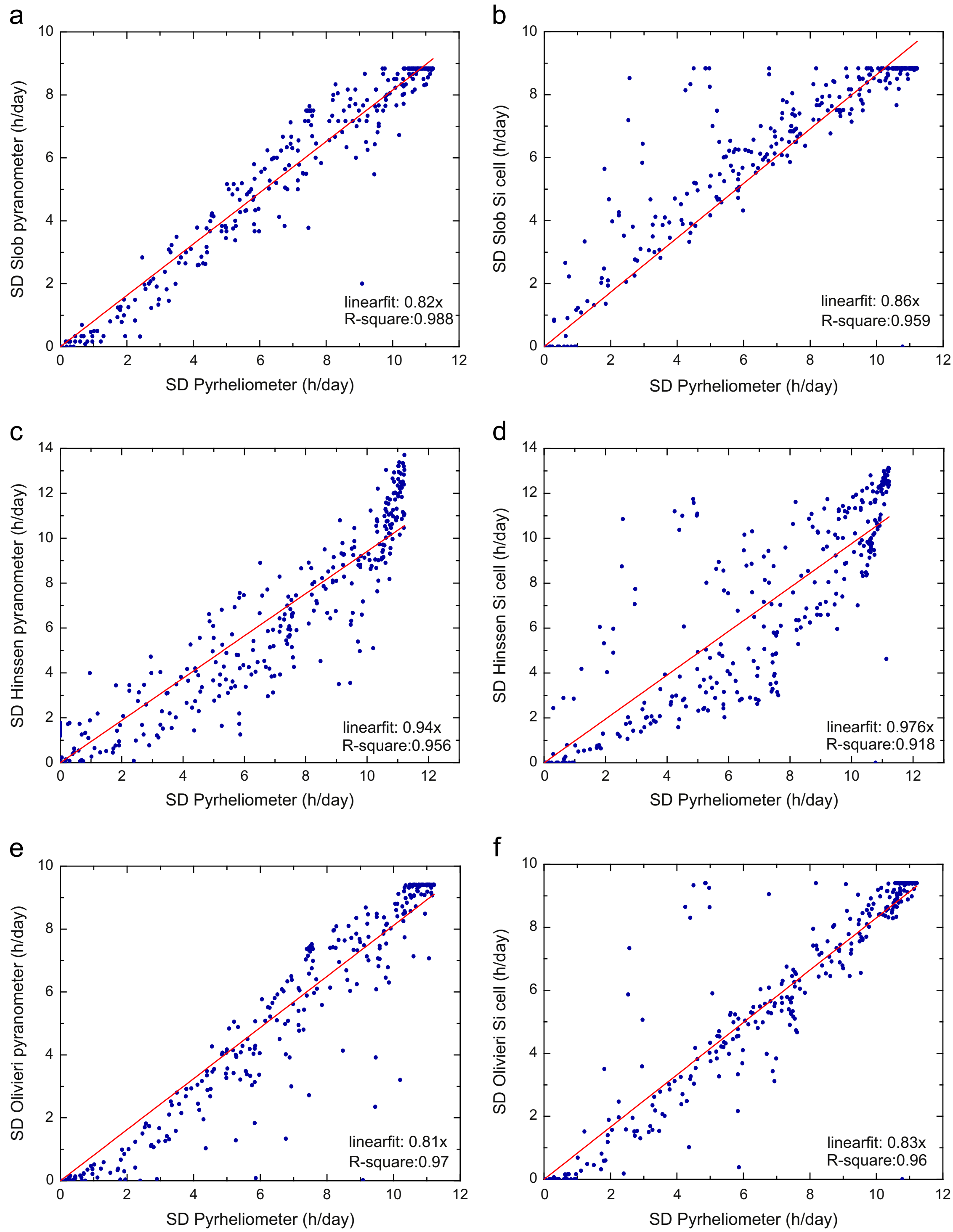


Fig. 4. Daily sunshine duration calculated with the three algorithms (Slob, Hinssen and Olivieri) vs. the sunshine duration calculated by the pyrheliomter for both the pyranometer (a, c and e) and the silicon solar cell (b, d and f), showing the correlation between them and the linear fitting.

comprehensively studied in the literature [11], as this algorithm starts considering sunshine when the elevation angle is above 5.7°. The Hinssen algorithm lowers this limit to 2.9° and the Olivieri to 3°. Another reason for underestimation in this particular study is due to the tilted surface of the pyranometer, which can result in it receiving less light at small elevation angles at sunrise and sunset, when the sun can be even behind the pyranometer. This is more critical even for the tilted solar cell, as it will not receive solar radiation at high azimuth solar angles. However, if the aim is to calculate sunshine duration for a particular surface tilted and positioned similarly to the silicon solar cell, and with and equivalent reduced field-of-view, it will be more accurate to use the solar cell than using the pyranometer. This is the same concept as used in photovoltaic power plants, using a calibrated solar cell of the same technology as the PV modules and in the same position to measure solar radiation gives the energy that the photovoltaic modules are able to convert into electricity (‘usable energy’), and therefore, production estimations and calculations are more accurate [31,32].

Fig. 5a gives the frequency distribution for the difference between the daily *SD* calculated by the solar cell using the Olivieri

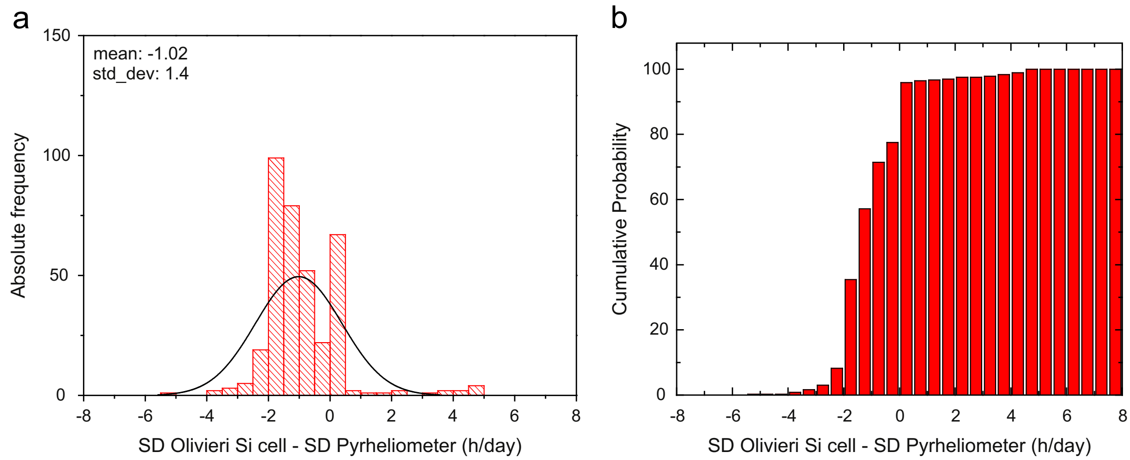


Fig. 5. (a) Absolute frequency of the difference between daily *SD* calculated with the Olivieri algorithm and the solar cell and the *SD* calculated with the pyrheliometer (h/day) and (b) cumulative probability of *SD* Olivieri Si cell – *SD* Pyrheliometer (h/day).

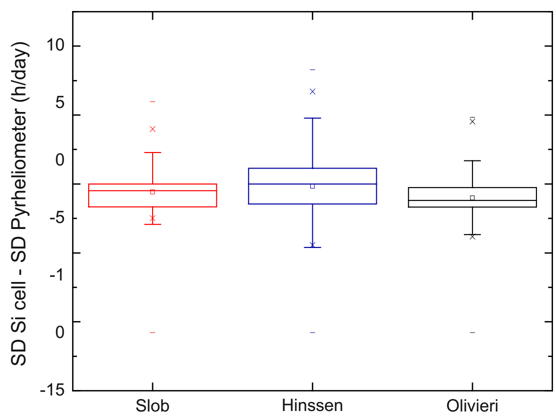


Fig. 6. Box plot of *SD* Si cell – *SD* Pyrheliometer (h/day) for the three algorithms, Slob, Hinssen and Olivieri, showing that the Olivieri algorithm gives the better adjustment for measuring *SD* with a photovoltaic solar cell.

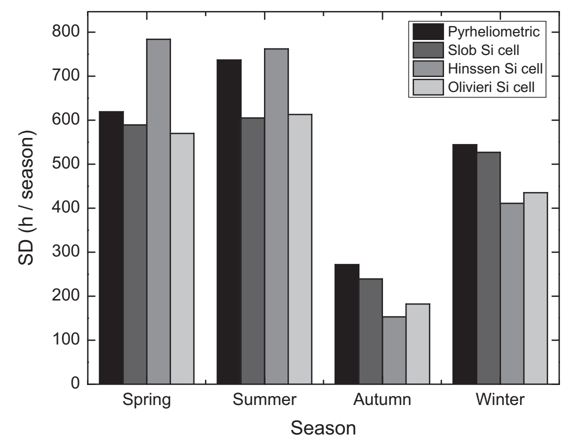


Fig. 7. Seasonal sunshine duration calculated by the pyrheliometer and the three pyranometric algorithms using the solar cell: Slob, Hinssen and Olivieri.

Table 2
Seasonal pyrheliometric sunshine duration and differences between the sunshine durations calculated by the three pyranometric algorithms using the solar cell. Autumn months have less total hours due to the reduced number of quality-data days due to technical problems.

	Spring	Summer	Autumn	Winter
SD Pyrheliometric (h)	619	737	272	544
SD Slob Si cell – *SD* Pyrh (h)	−30	−132	−33	−17
SD Hinssen Si cell – *SD* Pyrh (h)	165	25	−119	−133
SD Olivieri Si cell – *SD* Pyrh (h)	−49	−124	−90	−109

algorithm and the pyrheliometer. We can see how the *SD* is underestimated as most of the values are below zero. The daily mean difference is −1.02 h and the standard deviation is of 1.4 h. Fig. 5b shows the cumulative probability of the daily difference, with 95% of the values below +0.25 h of difference.

Fig. 6 shows the box plot of the differences between the daily *SD* calculated for the three algorithms using the solar cell and the *SD* calculated from the pyrheliometer. It shows again how the Olivieri algorithm is the most suitable for the measurement of sunshine duration with a photovoltaic solar cell.

Finally, analysing the sunshine duration calculated by the solar cell seasonally, separated into Spring (April–June), Summer (July–September), Autumn (October–December) and Winter (January–March), it can be observed that the Slob algorithm underperforms in the summer months, is similar in spring and autumn and improves in winter (Table 2 and Fig. 7). This agrees with the previous studies and analysis [2]. On the other hand, the Hinssen algorithm overestimates *SD* in spring and summer and underestimates *SD* substantially in autumn and winter, with high variation in adjustment. Finally, the Olivieri algorithm underestimates *SD* over the four seasons, showing greatest underestimation in the summer and winter months.

The tilted position of the cell, as discussed earlier, affects the performance of different algorithms, as well as the definition of the codes for different algorithms. It is important to observe that the algorithms were developed mostly in the Netherlands and Northern Europe, with different climatic conditions to those from the south of Europe, corresponding to the solar radiation data for this study. Previous studies have considered datasets with a yearly number of sunshine hours of about 1400, and the location in this study experiences about 2200 h. It is also expected that turbidity values vary considerably from one location to another, so this could also affect the performance of the algorithms.

4. Summary and conclusions

The objective of this work was to study if a PV silicon solar reference cell could be used to measure sunshine duration for low cost solar technologies applications. A comparison between the standard methods defined by the WMO, using a pyrheliometer to measure sunshine duration, and different algorithms when using a

single pyranometer, was conducted including the calculation of sunshine duration using a solar cell and the pyranometric algorithms.

The evaluation was performed using solar radiation data from the meteorological station and photovoltaic installation from the Photovoltaic Technology Group at the University of Cyprus, Nicosia, Cyprus, for the period December 2011–November 2012. Three pyranometric algorithms were used: the Slob and Monna, the Hinssen and Knap and the Olivieri methods. The algorithms were adapted to the tilted pyranometer and calibrated photovoltaic silicon solar cell from Cyprus. The pyrheliometric method gave an annual sunshine duration of 2171 h. The pyranometric methods provided annual sunshine durations differences of -145 h (-7%) and -61 h (-3%) for the Hinssen and Knap algorithm (pyranometer and cell); of -411 h (-19%) and -210 h (-10%) for the Slob and Monna; and of -457 h (-21%) and -372 h (-17%) for the Olivieri. All the algorithms underestimate sunshine duration over the span of a year and the results between the pyranometer and the solar cell were comparable.

On a daily difference mean basis, the Hinssen and Knap algorithm had an excessive dispersion and uncertainty in the *SD* values, (-0.4 ± 0.08 h/day ($\pm20\%$) and -0.17 ± 0.11 h/day ($\pm65\%$)). The Slob and Monna had less uncertainty but still high for the solar cell results (-1.12 ± 0.05 h/day ($\pm4\%$) for the pyranometer and -0.57 ± 0.08 h/day ($\pm14\%$) for the cell). Finally, the Olivieri algorithm gave a daily mean difference with the pyrheliometric method of -1.25 ± 0.06 h/day ($\pm5\%$) for the pyranometer and of -1.02 ± 0.07 h/day ($\pm7\%$) for the solar cell, both acceptable results and very similar between them.

The main conclusion is that the silicon solar cell is capable of measuring sunshine duration on a daily basis with an uncertainty similar to the obtained with a pyranometer when using the Olivieri algorithm. It can measure sunshine duration on a daily basis with an uncertainty of 1.4 h/day, which is sufficient for some applications. For example, in low-cost solar water purification, the device can be overexposed to the sun to reduce this uncertainty. Again, this difference and uncertainty value is relative to a pyrheliometer, and although it underestimates *SD*, a silicon cell might be more useful as it will give an indication of the real sunshine hours that a device with the same characteristics and limitations (same position, similar reduced field-of-view) as the solar cell is exposed to.

In terms of cost, the reduction could range from the current 3000€ per commercial calibrated pyranometer to the cost of a silicon solar cell (1–2€/cell plus the cost of calibration, depending on the requirements and the lab, up to 100–300€). Another issue is that all sunshine duration sensors, whether using pyranometers or not, require high accuracy datalogger systems. The current commercial systems can be up to 3000€, but in another note, low-cost dataloggers with high resolution for PV applications have been already developed using Arduino [33], with a total cost for the first prototypes of only 60€. This cost reduction, along with the good performance indicated previously, shows the high potential of using silicon solar cells as sunshine duration sensors in developing countries.

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